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(54) Apparatus for electron-beam irradiation of surfaces.

(57) This disclosure is concerned with a process of and apparatus for producing relatively low energy electron beams through pulsed cold-cathode beam generation in a mode of operation involving an important intermediate region of a substantially linear depth-dose profile characteristic that reduces the sensitivity to possible voltage variations, and with improved triggering structures that significantly improve reliability and minimize erractic pulse generation and missing pulses, thus particularly adapting the process and apparatus for such stringent applications as production-line sterilization of surfaces, materials or workpieces passed by the apparatus.

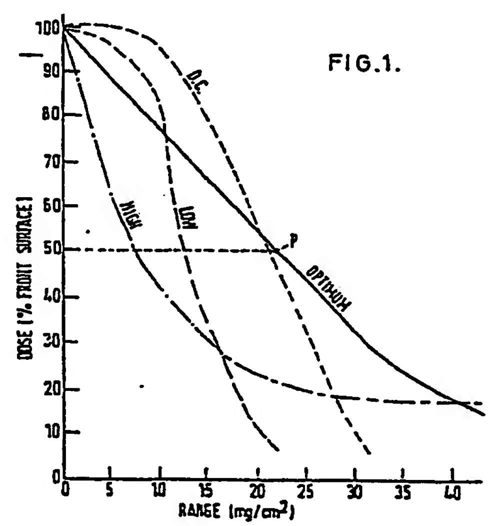

FIG.1.

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"Apparatus for Electron-Beam Irradiation of Surfaces"

FIELD OF THE INVENTION

The present invention relates to apparatus for electron-beam irradiation of surfaces such as in production-line sterilization of a product, particularly by cold-cathode pulsed electron-beam generation of relatively low energy electrons, say, of the order of 50-450 keV.

BACKGROUND OF THE INVENTION

Relatively low energy electron beams have been used successfully for surface sterilization as described, for example, in United States Letters Patent No. 3,780,308. Bulk electron-sterilization techniques are disclosed in U.S. Letters Patent No. 3,779,796. In such applications direct-current beam generators of the type marketed under the trademark "Electrocurtain", by Energy Sciences Inc., have been employed, such low energy electron beam generation being described, for example, in U.S. Letters Patent Nos. 3,702,412; 3,745,396; and 3,769,600.

There are advantages, in some applications, in the use of repetitive-pulse-production of relatively low energy electron beams with the aid of cold-cathode electron sources, and with capacitor-discharge pulsing techniques of the type previously used in other types of pulse generators, including the Marx-type capacitor storage-spark-discharge generators. Among the more recent uses has been in the pulsing of lasers, as described in Physics Today, April, 1975. (Also E. Ault et al, IEEE J. Quant, Elec., Vol.10, p.624, on [1974]).

Among the considerations in applying such techniques to the problems of the present invention, however, are the very serious consequences of even temporary erratic pulsing or the missing of pulses, which, when occurring in production-line sterilization, for example, can result in the potentially

dangerous effect of failure to sterilize, or improperly or inadequately sterilizing the workpiece as a result of poor beam uniformity and directivity. Increased reliability of these pulse techniques is thus required. Moreover prior systems using such pulse techniques were mostly employed in laboratory and experimental work which do not require the longevity of operation and industrial reliability sufficient to meet the commercial requirements of production-line sterilization.

It has been discovered that one of the main reasons for unreliability (for the present purposes) of previous pulse techniques has been the absence of a sufficiently wide triggering range of the spark-discharge gaps in the pulse generator or driving circuit. Previously, fixed gap trigger generators have operated as relatively narrow triggering ranges of approximately 15 percent below the self-breakdown voltages; or, where dynamic range variation has been required, with manual adjustments or gap spacing or by multiple triggered gaps, clearly unsuitable for production-line operation. Near the upper end of the triggering range, occasional prefires cause low output voltages, while near the lower end of the triggering range, occasional misses occur. In accordance with the present invention, on the other hand, triggering range capacity has been extended upwards of about 30 percent-operation which is necessary for long service life.

Among the novel pulsing circuit features of the invention, are significantly improved conductive shield structures for increasing the stray capacitance to ground along the capacitor stack, and large-area spark gaps of the "rail" type with novel trigger location and operation.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a new and improved apparatus for the generation of relatively low voltage,

energetic electron beam pulses which are not subject to the above-described limitations and disadvantages, but that possess the increased reliability needed for many industrial applications, such as sterilization, and that, in large measure is attained by a significantly increased triggering range and operation in a most-favoured region of a relatively low-slope depth-dose profile characteristic of the generated beam.

Another object of the invention is to provide a new and improved pulse-generating capacitor bank construction that allows for a greatly increased range of voltage variation within which operation of the system is permissible, and with a concomitant increase in reliability.

According to the invention there is provided apparatus for electron beam irradiation of a surface, such as in production-line sterilization of a product comprising electrically triggered repetitive pulse-generating means having a stacked array of discharge gaps connected with a corrsponding staggered co-extensive array of capacitors and disposed in a pressurized vessel; evacuated electron gun means provided with electron-pervious window means; means for electrically connecting the pulse-generating means to the electron gun means to draw therefrom electron-beams exiting the window means in response to the pulses generated by the pulse-generating means; and high voltage insulating means separating said pressurized vessel from said evacuated electron gun means and supporting said electrically connecting means.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example, with reference to the accompanying drawings wherein:

Figure 1 is a graph contrasting a dose-depth sterilization profile

characteristic attained in accordance with the invention with prior characteristics;

Figure 2 is a side elevation of electron beam sterilization apparatus construction in accordance with a preferred embodiment of the invention;

Figure 3 is a view of the lower right-hand portion of Figure 2, upon an enlarged scale, and partly sectionalized longitudinally, to illustrate details of the cold-cathode electron beam generators;

Figure 4 is a schematic circuit diagram of a preferred Marx-type pulse genrator for driving the beam generators of Figure 3;

Figure 5 is a longitudinal section, upon a larger scale, of the upper capacitor-spark gap Marx pulse generator of Figure 2 and of the circuit type shown in Figure 4; and

Figure 6 is a transverse section taken along the line 6-6 of Figure 5, looking in the direction of the arrows.

BEST MODE OF CARRYING OUT THE INVENTION

Before discussing the preferred apparatus and techniques of operation of the invention it will be helpful to consider a graphical representation of the characteristic obtained with the aid of the invention contrasted with the characteristics produced by prior known systems.

Accordingly the graph of Figure 1, shows delivered irradiation dose, as a percentage of front product surface, plotted along the ordinate, and range of penetration or depth into the product or other surface wall plotted along the abscissa in mg/cm^2. The remarkably linear, relatively low-or moderate-slope curve labelled "OPTIMUM" (having significant curvature only at its lower or right-hand end) represents the type of dose-depth profile characteristic attainable with the novel cold-cathode operation of the invention, as distinguished from those attainable with

prior art techniques discussed, for example, in said Letters Patent No. 3,780,308 (see more particularly Figure 1 thereof). Below and above such optimum conditions, as represented by the steep, non-linear dash-line curve "LOW" and the steep, non-linear dash-dot curve "HIGH", this characteristic is not attained. It is also not attained by machines such as the beforementioned "Electrocurtain" type D.C.generators, operating with the rather steep, non-linear curve "D.C." of Figure 1. By operating with as low a slope as possible at the intermediate (near or approximately one-half) dose point P, (say of the order of 45° slope, more or less, as distinguished from the steep angle slopes, including almost 90° slopes, of prior type characteristics of Figure 1) it has been discovered that the generation of substantially constant electron beam impulses with substantially reduced sensitivity to a wide range of possible voltage variations during the pulse generation is possible, thus remarkably ensuring substantially uniform irradiation of the products passing by the apparatus.

Such reduced sensitivity does not exist for the steep slope, non-linear profiles of the prior art as indicated at "LOW", "HIGH" and "D.C." in Figure 1, the slope of the curve being, indeed, a measure of the sensitivity to voltage changes. Through the obviating of such steep (and non-linear) profiles, the present invention enables reduced sensitivity to voltage variation. Operation up to and near the intermediate one-half dose point P enables the required depth of sterilization penetration (say, of the order of 20-25 mg/cm^2, Figure 1, or 0.2 to 0.25 mm of penetration in paper wall and the like). That is, the surfaces of the irradiation-penetrated product most remote from the electron beam window are treated near the one-half dose.

The use of pulsed cold-cathode operation, where appropriate, as distinguished from thermionic cathode operation, moreover, results in simplified electronics, lower insulation requirements, decrease in size due to pulse stress considerations, decrease in vacuum requirements for reliable operation, and a substantial

decrease in cost of the apparatus. Through the additional use of multiple pulse overlap to avoid the deleterious effects of even statistical spark-gap prefire or miss, such apparatus can provide a new order of reliability and uniform performance.

Referring to the generalized system of Figure 2, a pair of linear cold-cathode electrom beam generators 2 and 2' is shown mounted in general opposition. The respective electron-permeable windows 1 and 1' irradiate a web W and/or articles carried thereby, as schematically indicated by the arrays of arrows eliminating from 1 and 1', with the web W passing continuously into the plane of the drawing (through conventional nitrogen or other gas-contained chamber or zone, as discussed, for example, in said Letters Patent). An array of stacked capacitor-spark-gap Marx-type generator elements, later described, is disposed within an upper pressurized vessel M for driving the cold-cathode generators. A vacuum pump V is provided for the evacuated generating chambers 2 and 2', with the pulse feed conductor section F applying the periodic pulses to the cold-cathode diode structures, later more fully described, and with a cooling system comprising a heat exchanger H, pump P' and liquid reservoir R.

Turning, now, to the details of the irradiating generators 2 and 2', this section of the apparatus is shown, in Figure 3, on a larger scale than in Figure 2, and in longitudinal section. The driving pulses from the Marx generator in the upper pressurised vessel M are provided between an inner conductor 3 and the outer ground vessel wall, and are fed via a vertical conductor extension 3' within the evacuated chambers F to a pair of horizontal conductor supports 4 and 4' supporting the respective cold-cathode mounting structures, of which the mount 5 is shown within the chamber 2 (it being understood that a similar structure is provided within chamber 2'). The mount 5 supports the longitudinally extending field-initiated cold-cathode gun 6 (as, for example, of longitudinal parallel foild strips, such as of copper, graphite, or copper-

graphite composite), facing the longitudinal electron-pervious window 1; it being understood that the cathode of the gun within the chamber 2' will be upwardly pointing toward the window 1'. The grounded outer conductor-wall window of the chambers 2 and 2' constitute the anodes of the cold-cathode diode guns thus provided. Useful field-initiated cold cathode gun configurations are described, for example, by Loda and DeHart (HQ Defense Nuclear Agency), "investigation of pulsed cold cathode electron guns for use as a laser discharge sustainer", Physics International Company, DNA 2777F, May, 1972, PIFR-326.

The conical insulating bushing 7 supporting the conductors 3-3' on opposite sides of the apex seals the gas-pressurized chamber M of the spark-gap driving circuits from the vacuum section F-2-2' of the electron beam generators, providing a most convenient high-voltage bushing, as well.

While the windows 1 and 1' of the electron generators 2 and 2', generally oppose one another, they are rotated slightly relative to one another so that the existing beams are offset or staggered, through overlapping partially (say, of the order of one beam width) to avoid direct collision with one another or other beam interference, and, in a sterilizing application, to eliminate the possibility of transfer of organisms from one side of the web passed therebetween to the other.

It has been found that there is a most important relationship between the impedance match effected between the cold-cathode gun and the driver circuits, and the nature both of the depth-dose profile characteristic attained from the resulting electron beams and the pulse spectrum thereof. If the cold- cathode diode gun impedance to too low, the electron spectrum has been found to be dominated by low-energy electrons and the depth-dose pr file

deviates from the described "OPTIMUM" profile, as shown at "LOW" in Figure 1, whereas, if the gun impedance is too high, an excess of both low-and high-energy electrons results, with the depth-dose profile curve showing a low half-dose point (as shown at "HIGH" in Figure 1), but great penetrating power and energy waste thereafter. Through appropriate spacing of the plasma cathode 6 and anode walls, as well as the number and dimensions of the cathode foil strips, the match can be adjusted to attain the desired "OPTIMUM" profile characteristic, and adjustment of the pulse repetition rate can achieve operation which produces the novel results previously described.

It now remains to describe the preferred details of the capacitor-spark gap driver circuit, a simplified schematic diagram of which is illustrated in Figure 4. Capacitor banks C_1-C_2-etc. with associated spark gaps S_1-S_2-S_3, etc. forming a Marx-type generator, are charged from a high frequency inverter 30 working directly from line current rectified by a rectifier network 32, as opposed to conventional D.C. charging schemes where more than half of the input power is absorbed in the charging resistors. The high-frequencyinverter 30, with a high transformer A.C. voltage output (say, 15 K.v.ʌ ms at 10-20 KHz), drives a pair of conventional doubling circuits 36 of opposite polarity, with both polarities charged simultaneously through comparatively small series capacitors 38(say of the order of 100 picofarads) that pump up the much larger capactirs C_1, C_2 etc. through isolating resistors R_1. Stray capacitance and leakage reactance of the inverter output transformer are used to effect self-resonating in the inverter. The capacitor bank is arranged to charge both positively and negatively simultaneously balanced to ground. Such balanced charging reduced D.C. insulation requirements by one half. The output (transformer) of the inverter 30 is thus exposed to only the l ad of the small pump capacitors 38 and pumps charge through the same in both directions. However, each pump capacitor 38 connects to the bank capacitors C_1, etc. through a diode, so that the bank is charged in only one direction. The inverter can therefore operate into the bank at zero voltage, because the

current output of the inverter is limited by the reactance of the small capacitance.

A sensing resistor 42 measures the voltage on the capacitor bank and feeds back a signal to the trigger generator for comparison with a preset reference. When the charge-sensing signal reaches the preset level, the trigger generator 44 produces an output pulse, commonly in the range of 50 kv, applied to a trigger pin 46 which is situated in the first full gap or second stage S_2 of the pulse generator system. By triggering other than in the first stage S_1, which is conventional in such generators as described in the previously cited references, it has been found that a substantial increase in the effective triggering range of the system is obtained, the advantages of which have been previously mentioned. The first gap S_1, because it is greatly over-volted, breaks down after gap S_2 and then the Marx system fires down the line, over-volting S_3 through C_2 , etc. until the final driving pulse is delivered to the load R_{LOAD}, schematically representing the cold-cathode electron gun diodes.

A preferred construction is shown in Figure 5 and in the transverse section thereof in Figure 6, where the capacitors C_1, C_2, etc. of the bank are shown supported by vertical columns 20 on alternately opposite or staggered sides thereof (to reduce interstage coupling), with the spark gaps S_1, S_2 , S_3, etc. in a vertical column therebetween, flanked by columns of the charging resistors R_2,etc. The triggering pin 46 is shown associated with the second gap S_2, as before explained. Further, the assembly is surrounded by a downwardly and outwardly tapered conical conductor or shield S (actually in octagonal sections, Figure 6) which has been found to be as close a shielding arrangement as can be provided without breakdown problems and which materially reduces the volume occupied by the magnetic field set up during pulse generation, thus reducing the inductance significantly and desirably increasing capacitance to ground. This configuration has been found to aid in increasing

the triggering range, as before discussed.

In practical apparatus of this type, highly successful production-line sterilization has been obtained with 75 nanoseconds pulses (full width at half maximum amplitude), produced at a repetition rate of 20 pulses/second at 225 Kv peak voltage and 2 kiloamps peak current. The electon beam width at windows 1 and 1' was about 4.0 cm.. Synchronization of the line speed of the web W with the pulse repetition and dose-depth adjustments was effected such that for a 5 megarad surface dose, the line speed of the web W was adjusted to about 3 metres/minute, and the windows 1 and 1' of the gun cylinder generators 2 and 2' were tilted at about a 15° offset from facing one another. Under these conditions, a linear dose-depth profile close to that illustrated at "OPTIMUM" in Figure 1 was attained, and with at least about a 10-pulse overlap provided which, though the reliability of the system was very high, avoided even the remote statistical possibility of a spark-gap pre-breakdown or pulse miss, resulting in non-sterility of the irradiated product. As an example, B-pumilis, a radiation-resistant spore, was effectively destroyed (D_{10} - value of 250 kilorads; i.e. 20 log treatment). Voltage-pulse ranges of 200 1+ 50 Kv, with pulse widths (measured as before indicated) or the order of 80 1+20 nanoseconds, and with pulse repetition frequencies of the order of 20 1+ 10 pulses per second have been found most useful for certain sterilization purposes of the invention. Units involving products fed at higher line speeds (web speed of about 25 metres per minute) are operable at repetition frequencies of the order of 100 pulses per second. As before stated, low energy electrons of the order of 50 to 450 keV are useful for the purposes of the invention, being generated by electric-discharge pulses of the order of 100 to 500 kV: and with pulse widths at one-half maximum of the order of 50 to 150 nanoseconds, and repetition frequencies of the order of 20 to 100 pulses per second.

While the invention has been described in connection with its important application to cold-cathode beam sterilization, features of the same may be used in other applications where similar advantages are desired, and the novel aspects of circuit and constructional details may also be used elsewhere as desired; further modifications occurring to those skilled in the art being deemed to fall within the scope of the invention as defined in the appended claims.

CLAIMS

1. Apparatus for electron beam irradiation of a surface, such as in production-line sterilization of a product comprising electrically triggered repetitive pulse-generating means having a stacked array of discharge gaps connected with a corresponding staggered co-extensive array of capacitors and disposed in a pressurized vessel; evacuated electron gun means provided with electron-pervious window means; means for electrically connecting the pulse-generating means to the electron gun means tc effect discharge therefrom of electron-beams exiting the window means in response to the pulses generated by the pulse-generating means; and high-voltage insulating means separating said pressurized vessel from said evacuated electron gun means and supporting said electrically connecting means.

2. Apparatus for electron beam irradiation of a surface, such as in production-line sterilization of a product comprising electric-discharge repetitive pulse-generating means comprising Marx-type generation means having a stacked array of discharge gaps connected with a corresponding staggered co-extensive array of capacitors and means for initially triggering other than the first of said discharge gaps to effect the pulse generation; longitudinally extending electron gun means provided with longitudinally extending electron-pervious window means; and means for electrically connecting the pluse-generating means to the electron gun means to effect discharge therefrom of longitudinal strip-type electron-beams exiting the window means in response to the pulses generated by the pulse-generating means.

3. Apparatus as claimed in Claim 2 and in which there is provided conducting shield means surrounding said array of discharge gaps and capacitors and of successively increasing taper along said array.

4. Apparatus as claimed in Claim 2 and in which the discharge gaps and corresponding capacitor arrays are disposed within a pressurized housing, and said electron gun means are evacuated.

5. Apparatus as claimed in Claim 2 and in which there is provided a charging circuit operative from line current and connected with the capacitors, comprising rectifying means connected to the line current, high-frequency inverter means connected to the rectifying means for producing a high A.C. voltage output, and voltage doubler circuit means to receive said output.

6. Apparatus as claimed in Claim 5 and in which said voltage doubler circuit means comprises pump capacitor means and bank capacitor means, the former being of small capacitance value relative to the capacitance of the bank capacitor means, and the latter serving as a capacitor of the said array of capacitors.

7. Apparatus as claimed in Claim 2 and in which said pulse-generating means further comprises means for producing repetitive triggering pulses, and wherein there is provided trigger electrode means associated with the second of the discharge gaps and connected with the triggering pulse producing means.

8. Apparatus as claimed in Claim 2 and in which the said array of discharge gaps comprises a stack of substantially parallel pairs of spaced longitudinal rails.

9. Apparatus as claimed in Claim 2 and in which said electron guns means comprises a pair of electron guns disposed with their respective window means directed to different portions of a product-to-be-irradiated drawn by said window means.

10. Apparatus as claimed in Claim 9 and in which said pair of electron guns is adjusted so that the beams exiting their respective window means partially overlap.

11. Apparatus as claimed in Claim 9 and in which said beams are directed generally toward opposite sides of said product-to-be-irradiated.

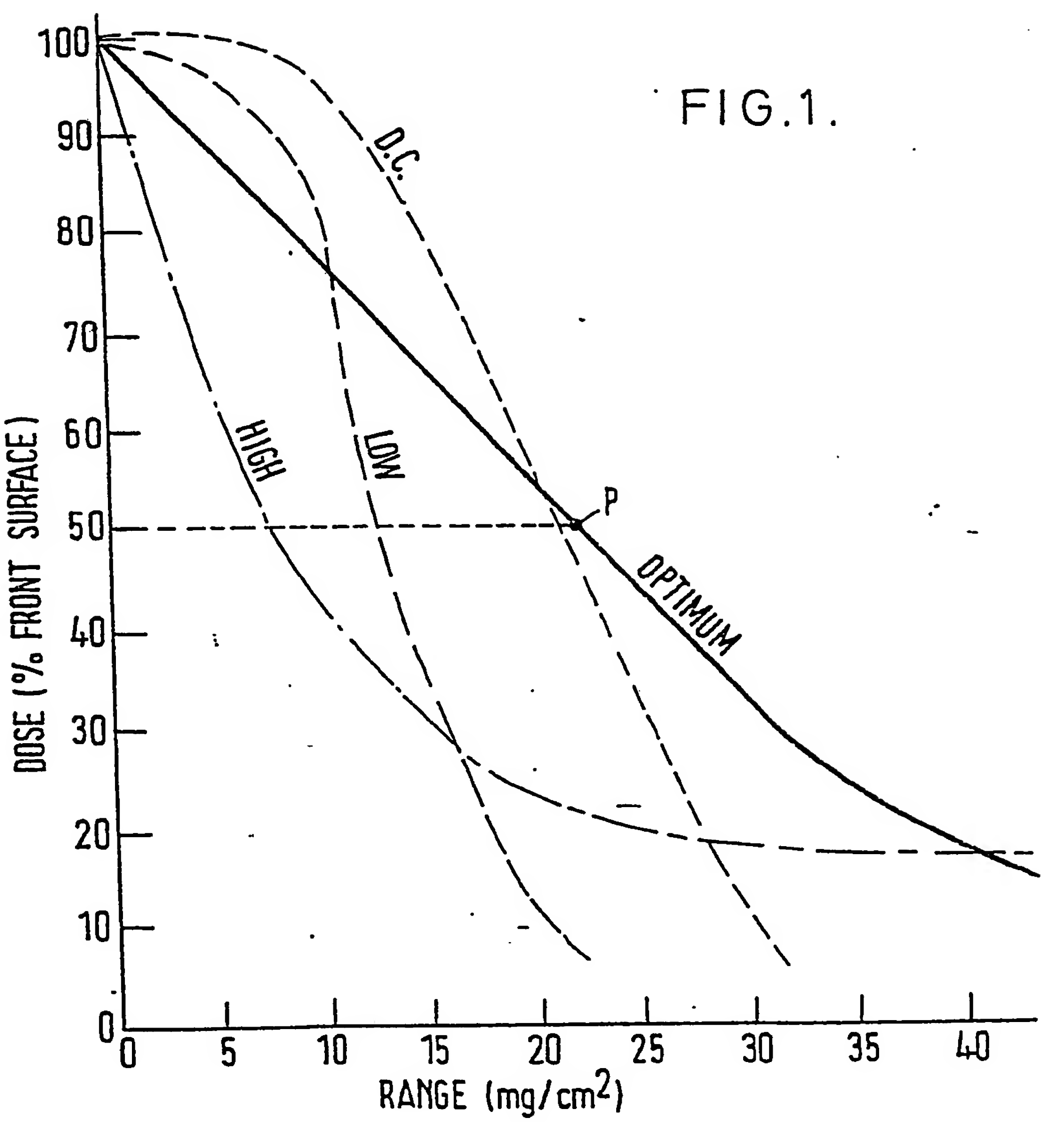
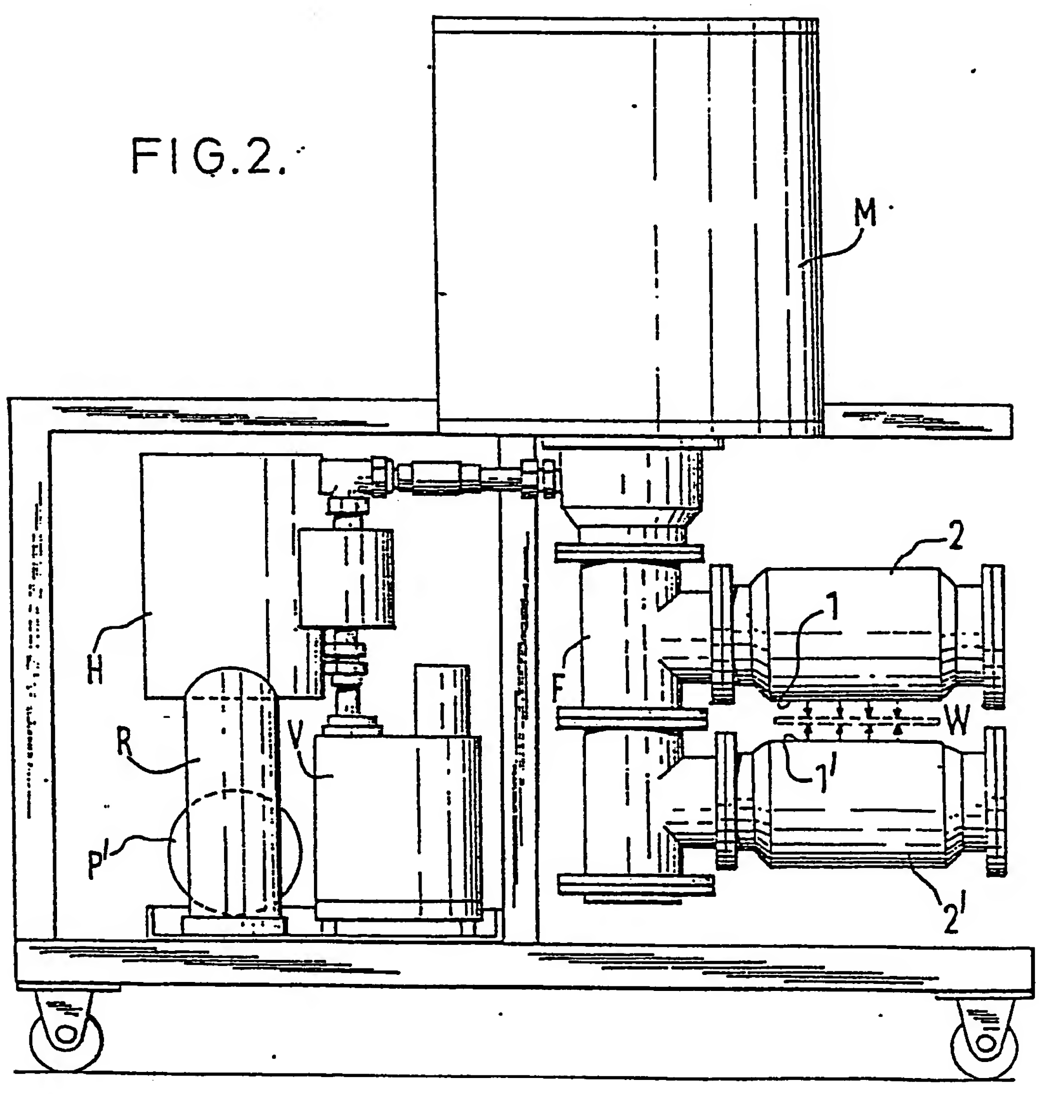


FIG.1.
D.C.
LOW
HIGH
P
OPTIMUM
DOSE (% FRONT SURFACE)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
RANGE (mg/cm2)

FIG.2.



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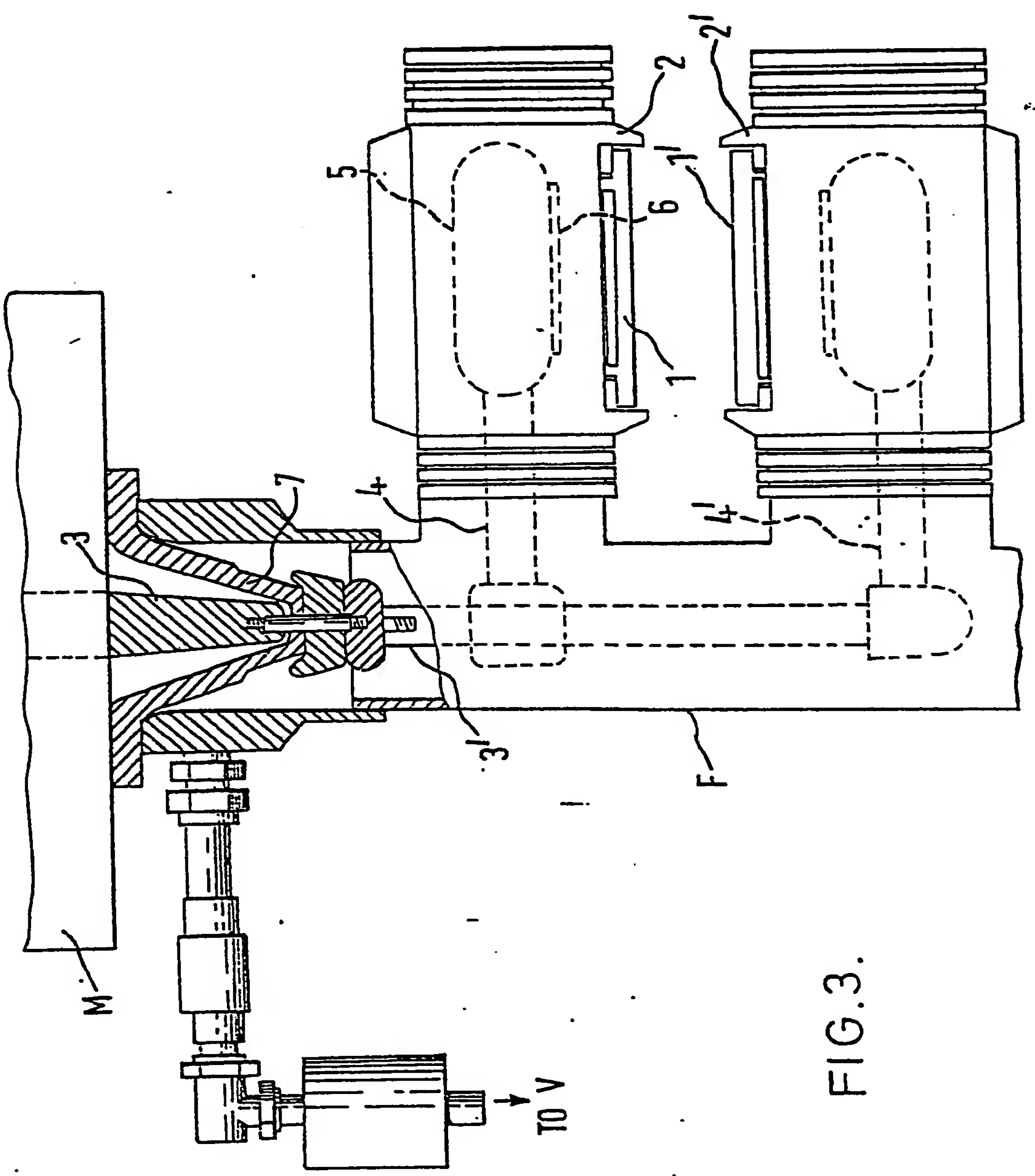

FIG.3.

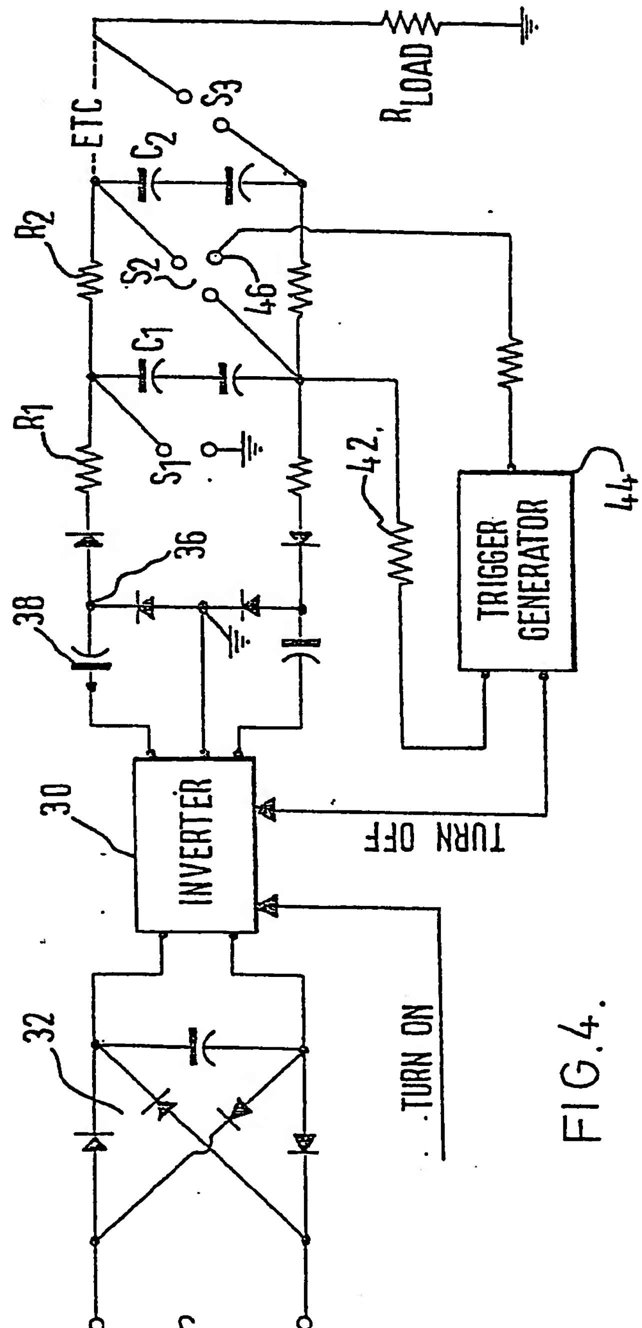
ETC
C_2
R_2
S_2
S_3
R_{LOAD}
46
C_1
R_1
S_1
42
44
TRIGGER GENERATOR
36
38
30
INVERTER
TURN OFF
TURN ON
32
S

FIG.4.

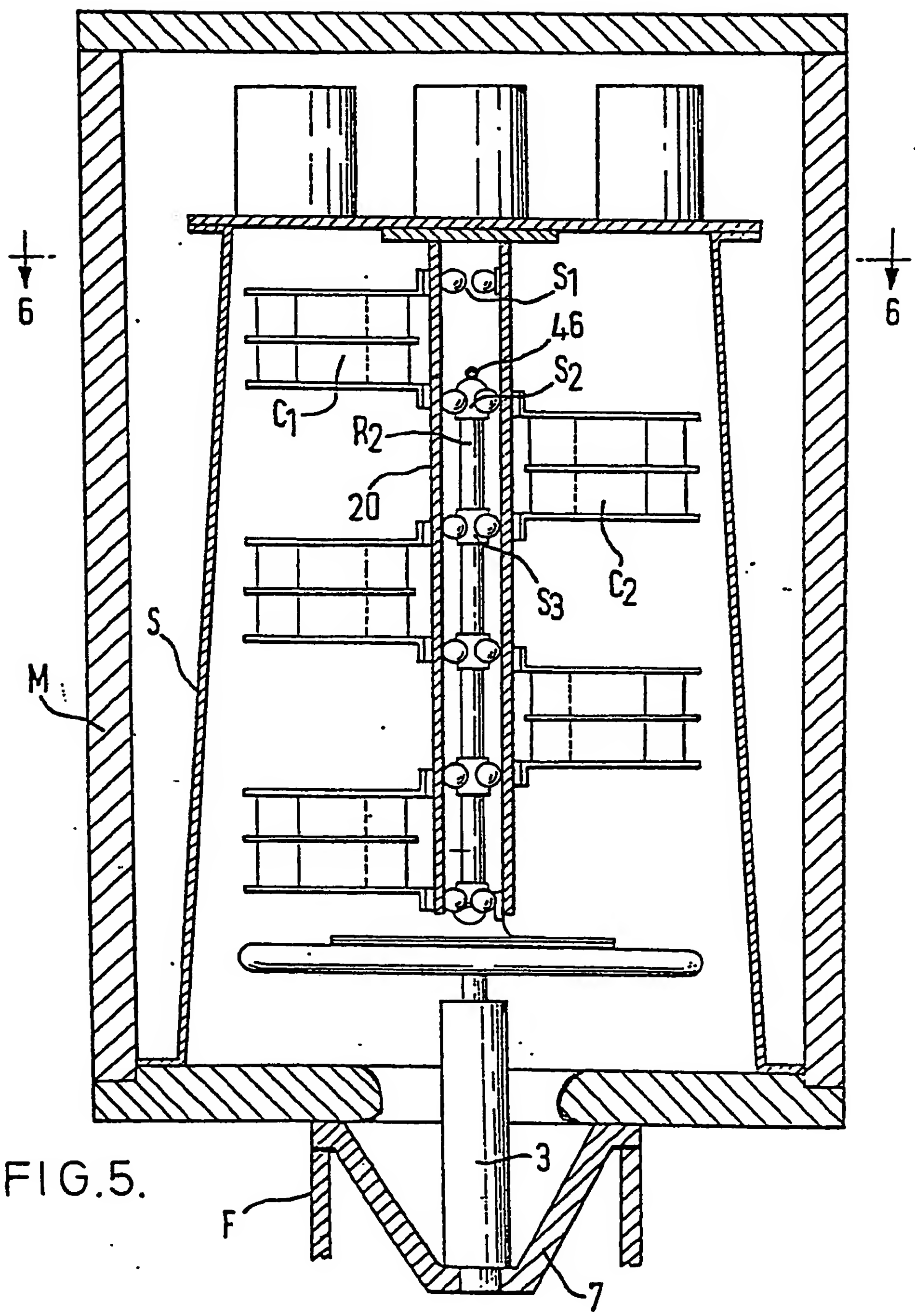

FIG.5.

FIG.6.